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A review of strategies for the control of high temperature stagnation in solar collectors and systems

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Abstract

High temperatures occurring during stagnation conditions can be very detrimental to the reliability, durability and safety of solar thermal systems. Various approaches to mitigate the effects to stagnation have been employed in the past, however as collector and system efficiencies improve, and larger solar systems are installed, the need for reliable and cost effective stagnation control schemes is increasing. In this paper, the impacts of stagnation and various approaches to stagnation control are discussed and compared with regard to their features and limitations.

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Keywords: Stagnation temperature contol; solar thermal systems; solar collectors; overtemperature contol

1. Introduction

With modern solar thermal systems, there exists the potential to reach very high temperatures during high solar irradiance conditions. Even mid-temperature flat-plate solar collectors may reach temperatures in excess of 180°C [1] during no-flow conditions caused by power or equipment failures or during routine shut-downs when there is a reduced energy demand. During these periods, referred to as stagnation conditions, there is the potential to seriously damage solar collectors or system components, accelerate the degradation of materials and heat transfer fluids, and even lead to user scalding. While the latter may be controlled by mixing valves, loss of performance and system degradation is more difficult to control.

Nomenclature

A, B	Collector performance coefficients derived by standard test, (W/m^2 K), (W/m^2 K^2)
ΔT_{ex}	Excess temperature due to collector stagnation, K
F_R	Collector heat removal factor

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G	Incident solar radiation level, W/m^2
T_a	Ambient temperature, °C
T_f	Collector heat transfer fluid temperature, °C
T_p	Collector absorber plate temperature, °C
U_L	Solar collector overall heat loss coefficient, (W/m^2 K)
η	Solar collector thermal efficiency
$(\tau\alpha)_e$	Solar collector effective transmission-absorptance product

Issues related to stagnation temperature control have existed for the last 25 years however, as collector and system efficiencies increase, the industry has renewed interest in finding suitable methods to alleviate these potentially damaging conditions [2].

Over the years, solar collector and system designers have developed a number of schemes to minimize the impact of stagnation conditions. This paper summarizes these concepts and discusses their features and limitations with regard to their use in both small and large scale solar thermal systems. Various concepts are reviewed based on a number of criteria, including: level of protection (e.g., collector versus system); fail-safe operation; cost and performance impacts.

2. Estimating stagnation temperatures

Stagnation occurs when the solar energy absorbed by a solar collector exceeds the capability of its heat transfer fluid circuit to adequately cool it, resulting in excessive absorber temperatures. This situation is most severe when the flow of heat transfer fluid through the collector is interrupted due to power outages, component failures or during periods of low heat demand. During these periods, the absorber plate will rapidly increase in temperature until its temperature is high enough to reject heat to the surrounding ambient by conduction, convection and radiation through the solar collector housing. As most solar thermal devices are designed to minimize heat losses to the surroundings, the absorber must therefore reach sufficiently high temperatures to compensate of the relatively high thermal resistance of the collector housing.

The magnitude of the (absorber) stagnation temperature is therefore highly dependent on the design and construction of the solar collector. Solar collectors designed with low heat-loss coefficients (e.g., evacuated or vacuum tube solar collectors) will normally have higher stagnation temperatures than those designed with higher heat loss coefficients (e.g., unglazed swimming pool collectors). In addition, as manufacturers strive to increase solar collector thermal efficiency by reducing heat losses from solar collectors, an unfortunate consequence is increasing stagnation temperatures.

Accurate stagnation temperatures can be measured or calculated by detailed heat transfer analysis, however, it is standard practice to estimate a solar collector's stagnation temperature based on the simplified "Hottel, Whillier, Bliss" performance characteristic [3] where solar collector thermal efficiency, η, is represented as a linear function of the temperature difference between the collector-coolant mean- or inlet-fluid temperature and the surrounding ambient temperature, divided by the solar insolation level, G (i.e., $(T_f-T_a)/G$), e.g.,

$$\eta = F_R(\tau\alpha)_e - F_R U_L (T_f - T_a)/G \tag{1}$$

By assuming the efficiency equals zero during stagnation, and approximating the absorber plate temperature as the fluid temperature, $T_p \approx T_f$, the stagnation temperature is usually estimated from

$$F_R(\tau\alpha)_e G = F_R U_L (T_p - T_a), \tag{2}$$

or

$$T_p \approx \frac{G(\tau\alpha)_e}{U_L} + T_a \tag{3}$$

Implicit in this calculation is that solar collector overall heat loss coefficient, $U_{L,}$ is constant. However, for most solar collectors, U_L is not constant but depends on a number of factors, including collector tilt, absolute absorber and air temperature, wind speed and effective sky temperature [3]. To account for the temperature dependence of the heat loss it is common to approximate the value of U_L as linear function of the temperature difference between the absorber plate and the ambient temperature, i.e.,

$$U_L = A + B * \left(T_f - T_a\right) \tag{4}$$

Once again letting $T_p \approx T_f$ and substituting this relationship into Eq. 2 above gives,

$$F_R\left(\tau\alpha\right)_e G = \left[A + B*(Tp - T_a)\right] * \left(Tp - T_a\right) \tag{5}$$

$$= A * \left(Tp - T_a\right) + B * \left(Tp - T_a\right)^2 \tag{6}$$

Letting $(T_p - T_a) = \Delta T_{ex}$, the excess stagnation temperature above Ta, results in a second-order (i.e., quadratic) polynomial equation, that can be solved to estimate ΔT_{ex} as a function of the collector coefficients: A, B, $F_R(\tau\alpha)_e$, and solar insolation level, G, e.g.,

$$B * \left(\Delta T_{ex}\right)^2 + A * \left(\Delta T_{ex}\right) - F_R\left(\tau\alpha\right)_e G = 0 \tag{7}$$

The coefficients $F_R(\tau\alpha)_{e,}$ A, B are normally derived from experimental data obtained during routine testing to determine a particular solar collector's thermal performance rating or characteristic performance curve [4, 5].

To illustrate this calculation, the performance coefficients of three typical, commercially available, solar collectors were used to estimate their stagnation temperatures as a function of solar insolation level, G. The solar collectors considered consisted of a high performance evacuated-tube solar collector (*ETC*), a medium–temperature, mid-performance flat plate solar collector (*MPFP*) and a low-temperature, low-performance flat plate solar collector (*LPFP*). Table 1 summarizes the characteristics of these collectors based on data obtained from SRCC published data [5] and lists the estimated stagnation temperatures derived from these values at solar insolation level of 1000 W/m^2 and a surrounding ambient air temperature of 30^{o}C. Estimated stagnation temperatures for the three collectors listed in Table 1 are also plotted as a function of the solar radiation level incident on the solar collector surface, G.

3. Consequences of solar collector stagnation

During stagnation conditions, there is the potential to seriously damage solar collectors or system components, accelerate the degradation of materials and heat transfer fluids, and even lead to user scalding. The detrimental effects of stagnation conditions can occur both on a solar collector and solar system level.

Table 1. Estimated stagnation temperatures for three example solar collectors

Solar Collector Type	Collector Performance Parameters [5]	ΔT_{ex} at G=1000 W/m^2	Stagnation Temperature at Ta=30^{o}C
Evacuated Tube Solar collector (*ETC*) (Selective absorber)	$F_R(\tau\alpha)_e = 0.48$, $A = 1.094$, $B = 0.0015$ (Linear Para. $F_R(\tau\alpha)_e = 0.481$, $F_RU_L = 1.127$ W/m^{2}K)	320 K	350^{o}C
Mid-performance flat-plate, (*MPFP*) (Single glazing, selective absorber)	$F_R(\tau\alpha)_e = 0.762$, $A = 3.279$, $B = 0.0129$ (Linear Para. $F_R(\tau\alpha)_e = 0.768$, $F_RU_L = 4.035$ W/m^{2}K)	147 K	177^{o}C
Low-performance flat-plate (*LPFP*) (Single glazing, non-selective absorber)	$F_R(\tau\alpha)_e = 0.737$, $A = 4.419$, $B = 0.0503$ (Linear Para. $F_R(\tau\alpha)_e = 0.772$, $F_RU_L = 8.360$ W/m^{2}K)	85 K	115^{o}C

3.1. Solar collector effects

As indicated in Section 2, during stagnation, the absorber plate of a solar collector will reach high temperatures. In equilibrium, the absorber will reach temperatures high enough to drive a sufficient heat loss rate such that the collector thermal losses equal the solar energy input to the collector. Consequently, the magnitude of the stagnation temperature for any solar collector depends on solar insolation level and the ambient air temperature, Fig.1.

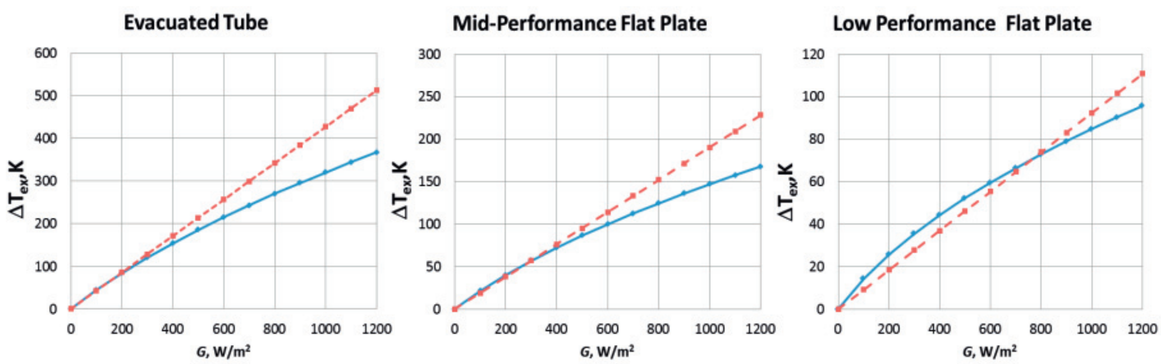

Fig. 1. Stagnation excess temperature, ΔT_{ex}, as a function of incident solar insolation level for three types of solar collector, as estimated from a linear (dashed lines) and a non-linear performance characteristics (solid lines). Values of ΔT_{ex} should be added to the ambient air-temperature to arrive at the predicted collector stagnation temperature

Extreme absorber temperatures may have detrimental effects on solar collectors, including the accelerated degradation of absorber coatings and materials [1]. Damage can span from deterioration of the visual appearance to degradation of the optical properties of the absorber coating, or both. In addition, high absorber temperatures may produce excessive stresses on absorber mountings or within the absorber structure itself (due to thermal expansion), particularly if different materials or complex geometries are used, Fig. 2. High temperatures in other components of the solar collector (e.g., insulation, gaskets and sealants) may also result in accelerated material degradation or outgassing of volatile compounds that may condense on the optical surfaces of the collector, (e.g., the surface of absorber or the interior of glazings).

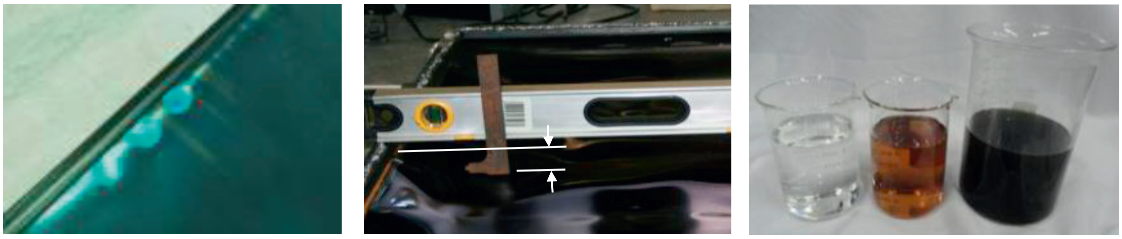

Fig. 2. (LHS) Deformation and bending of absorber plate at edge due to its constrained thermal expansion during stagnation; (Center) permanent deflection of absorber plate due to constrained thermal expansion of solar collector absorber plate; (RHS) degradation of propylene-glycol/water solution after increased time-exposure to high temperatures

3.2. Solar array and system level effects

During stagnation, high solar collector temperatures will increase pressures in solar collector arrays and their circulation loops. With closed-loop indirect solar systems, fluid expansion is usually handled with suitably sized expansion vessels that accommodate fluid expansion as temperature increases. However, as the temperature rises to excessive levels, pressure may reach levels that exceed the limits of pressure-release safety values, resulting in the release of fluid or venting of heat transfer fluid to the atmosphere. As systems later cool, the fluid circulation loops may be deficient of fluid leading to further overheating, pumping and fluid circulation problems. In addition, the release of high temperature and pressure fluid to the atmosphere may represent a safety risk as the fluid flashes to steam or vapor.

Other problems have been reported with regard to the restarting of large solar arrays that have been stagnating. In addition to the obvious issues related to accommodating for the thermal expansion of solar array headers and pipe runs at high temperatures, other problems may occur. In particular, the sudden pressure drop associated with the inflow of cold liquid may lead to thermal shock and stresses associated with the rapid boiling/vaporization/condensation of the heat transfer fluid [5]. The formation of vapor-locks and water-hammer has also been reported during system stagnation [6]. The transport of very high temperature heat transfer fluid to other components in the solar system (pumps, expansion tanks, heat exchangers etc.) may also be damaging or accelerate their failure [7]. Another concern is the potential to produce high temperatures at the distribution point to the end-user.

High stagnation temperatures may be particularly harmful in systems designed with collector loops filled with anti-freeze heat transfer fluids. Glycol based water solutions thermally degrade, resulting in deceased PH levels that accelerating corrosion [8] and material failure, Fig. 2 (RHS). Industrial grade heat transfer fluids are often buffered or inhibited to retard their degradation at high temperatures, however, for potable water systems, local health codes often require that non-toxic, uninhibited anti-freeze solutions be used that are not designed to withstand prolonged exposure to high temperatures.

3.3. The costs of stagnation

Quantifying the life cycle costs of stagnation is not easily done. In the case of situations where catastrophic failures have occurred due to thermal shocks or loss of coolant, the costs of repair, replacement or collateral damage may be readily apparent and may carry with them property or personal liability expenses. Other costs may be more difficult to quantify in the short term and include decreased thermal performance, the loss of operational time and energy due to increased maintenance or shut down periods. The reduction of component life, due to the degradation of materials in solar collectors, piping, insulation, expansion tanks and heat exchangers is also difficult to quantify and will depend on system load and local climate conditions. While the costs of the replacement of anti-freeze heat-transfer solutions in large commercial systems may be very significant, increased service and maintenance costs in small residential systems will significantly strip away the life-cycle economic returns of such systems.

Stagnation control schemes also carry with them a cost of implementation. Costs vary depending on the approach used and level of stagnation protection desired.

4. Approaches to stagnation control

Many approaches have been tried in the past to control stagnation temperatures and can be classified as: Collector, Array and System level, Fig. 3. Some are based on purposely degrading collector optical or thermal performance during stagnation or adding heat dumps to reject excess energy. Other approaches include modifying system operation and controls to waste excess heat at night or to purge the collector loop with low temperature fluid. The approaches taken often depend on the type of system, its location, and its end-use or load, e.g., domestic hot water heating, combi-systems or industrial process heat, etc.

In general, approaches to stagnation control vary by climatic region and are affected by other system design aspects such as freeze protection schemes, system design temperatures, loads and collector type. For example, systems designed to provide winter heating and year-round domestic hot water heating may be significantly over-sized during the summer months and susceptible to stagnation periods [8]. Seasonal storage schemes can eliminate the saturation associated with short-term thermal storage schemes but are expensive and are still susceptible to pump and power outages. In addition, systems designed for solar thermal cooling or industrial process heating may be equipped with high performance flat-plate or evacuated tube collectors that have the potential to reach very high stagnation temperatures and collector–loop pressures if not controlled.

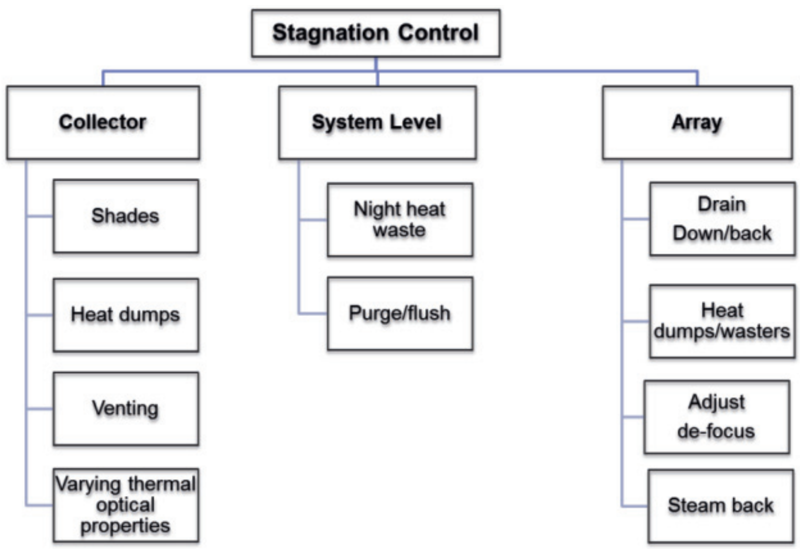

Fig. 3. Illustration of the various approaches taken to control or minimize stagnation conditions at the solar collector, the system level (i.e., operational), or solar array level

4.1. System level approaches to stagnation control

Approaches to stagnation control have been proposed for large solar arrays including: predictive control schemes designed to reject excess energy during night times [9]; the use of recirculation to waste heat; or fluid purging to cool overheated solar arrays. Dumping of heat from a saturated thermal storage by running the collector loop at night potentially wastes collected solar energy, consumes pump power and may be ineffective depending on the heat loss rate from the solar collector array [9].

If the system is cooled by purging the collector array or thermal storage with cooler fluid (e.g., mains water) significant energy and fluid may be wasted which may be undesirable in certain jurisdictions where fresh water is in short supply. In large scale district heating system one approach has been to dump excess heat to the district heating loop if stagnation should occur. In most cases auxiliary power must be available to power pumps and controls.

If functioning correctly, these schemes should protect solar arrays but may require backup power supplies to power pumps and controllers in the case of power outages. The latter components may increase system cost significantly and lead to increased complexity.

4.2. Collector loop approaches to control

In addition the approaches mentioned above, a number of methods have been employed to protect the collector loop and thereby minimize stagnation effects on complete solar systems. In large commercial solar arrays, system designers are increasingly specifying active heat dumps or “heat wasters” to reject excess energy to the environment. These usually consist of a control and valving system that diverts the collector loop flow to a fan-coil unit (e.g., dry cooler) that rejects excess heat to the atmospheric, Fig. 4. To protect against power outages, auxiliary power sources will be required to power the controls, pumps and fans [10]. Heat wasters using natural convection rather than forced (fan) circulation have been tried in an effort to reduce power consumption but require significant heat transfer surface area to adequately cool large collector arrays, Fig. 5. The cost of these auxiliary systems can be high with values reported as approaching \$US100/m^2 of collector area. More recently small scale “heat wasters” for residential domestic hot water systems have been proposed however most require the use of a circulation pump and auxiliary power source.

Fig. 4. Industrial scale ETC solar array (LHS) with large fan-coil “heat waster” unit (Center) and its “back-up” generator (RHS) to power the controls, pumps and fan during power outage [10]

Alternative approaches to minimize system level stagnation effects including the drain-down, drain-back or steam-back of the heat transfer fluid during stagnation conditions. These approaches effectively isolate the solar collector array from the balance of the system however they still expose the solar collector array to high stagnation temperatures. In drain-down or drain-back systems, care must be taken to ensure that air does not routinely enter the system as it may accelerate corrosion or contribute to biological growth in the system.

Fig. 5. Institutional solar collector array with rack-mounted convector heat waster

In closed solar collector loops intended for use in non-freezing climates, water may be used as a heat transfer fluid, however, in freeze-prone climates, glycol-based anti-freeze solutions are usually used in indirect solar systems with closed-loop collector arrays. Glycol-based antifreeze solutions are particularly susceptible to high stagnation conditions, but have been used in drain-back and steam-back systems in moderate climates [11]; however, their chemical stability in more extreme climates has not been demonstrated.

It has also been argued that heat transfer fluid residues on solar collector tube walls will be degraded by exposure to stagnation conditions although some heat transfer fluids are chemically "buffered" with inhibitors to counteract chemical degradation [8]. Increasingly, however, for potable water systems, code issues surrounding the toxicity use of chemical inhibitors and buffers exist and require the use of non-toxic heat transfer fluids in many jurisdictions. The lack of inhibitors severely limits the ability of glycol-based heat transfer fluids to withstand periodic stagnation periods.

When using drain-back and steam-back systems care must be taken to ensure that the system is installed such that vapor locks do not form in the collector loop or that other system components (e.g., valves, pumps and expansion vessels, etc.) are not exposed to excessive temperatures [7]. As well, steam-back schemes require the expansion vessel in the collector loop be sufficiently large to accommodate the vapor generated by the boiling of the heat transfer fluid from the solar collector array.

4.3. Solar collector approaches to stagnation control

A number of approaches have been proposed to limit stagnation conditions directly at the solar collector. This has the advantage of eliminating extra heat dumping equipment and also reduces the thermal stresses of the other system components. The simplest approach that has been suggested is to cover the solar collectors during stagnation conditions. While effective, the impracticality of this solution is reasonably obvious. Automated shading systems have been proposed but have the potential to be costly and unreliable, particularly in regions with snow cover during part of the year, Fig. 6.

4.3.1. Collector integral stagnation control

A number of configurations for rejecting heat directly from a solar collector during stagnation have been developed. These approaches address stagnation at the source and have the advantage of maintaining lower collector temperatures during stagnation, thereby eliminating the harmful effects of excessive temperatures e.g., thermal stresses, over-pressures, material and heat transfer fluid degradation, etc. If properly implemented, collector performance will be unaffected during normal operation and the use of additional costly heat dump hardware can be avoided.

Two commercially available approaches are shown in Fig. 7. One approach is to add an integral heat waster circuit in the solar collector that transports excess energy to the surrounding ambient. With such approaches it is desirable to have a mechanism that passively removes heat from the absorber during stagnation and therefore is not dependent of auxiliary power sources. In addition, it should not significantly increase complexity or cost.

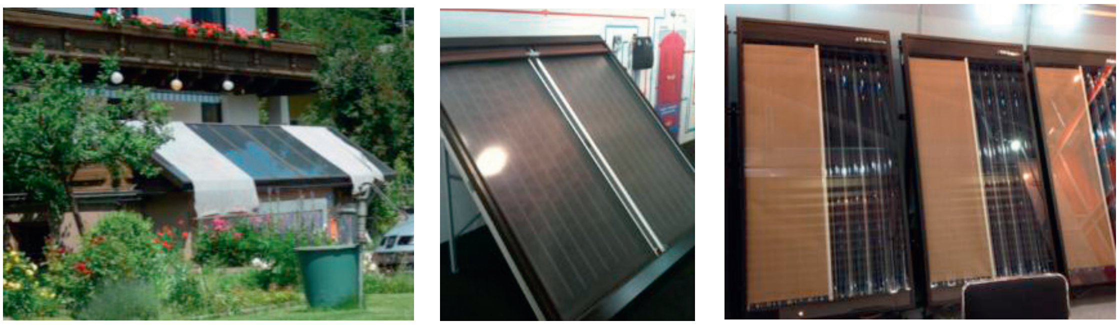

Fig. 6. Examples of shading systems implemented to control collector and system over-temperature due to stagnation. (LHS) home-owner solution for combi-system, (Center) manufacturer supplied external roller shades, (RHS) hybrid evacuated tube collectors with external collector housing and integral motorized horizontal shades

A second approach is to vent the solar collector housing during stagnation conditions allowing ambient air to ventilate and cool the solar absorber during stagnation conditions. If venting is driven by natural convection to avoid the use of fans, significant air flow and heat transfer area is required to adequately limit absorber temperatures. Schemes that vent the cavity between the solar collector absorber and glazing have been used for low temperatures collectors but may introduce atmospheric contaminants and moisture into this optical assembly. Venting of the underside of the absorber plate has been demonstrated to limit solar collector temperatures while not risking contamination of the optical surfaces of the collector [12], however, successful implementation of this scheme requires enhancement of the heat transfer rate on the undersurface of the solar absorber. These schemes also rely on a reliable and low cost valve assemble to eliminate venting during normal operation. Successful implementation of this approach has been demonstrated and implemented on commercially available solar collectors.

Fig 7. (LHS) Heat waster integrated into rear of high performance flat plate solar collector [13]; (RHS) Thermostatic valve of integral venting channel located at the top underside of a flat-plate solar collector (RHS) [12]

4.3.2. Stagnation control in high performance collectors

High performance solar collectors such as concentrating solar collectors, evacuated tube and high performance flat plates (e.g., flat plate collectors equipped with honeycomb convection suppression devices [13]) are subject to extremely high stagnation temperatures. In the case of concentrating collectors it common to defocus or misalign the solar collector to avoid stagnation conditions, however, these systems must have a rapid response and be “fail safe” or catastrophic failures may occur.

Schemes that do not require power, motors or fans are preferable due to their reliability and passive operation. Thermally actuated springs or shape-memory alloys have been used for collector stagnation controls in both flat plate and evacuated tube collectors [12, 14]. The use of an integral stagnation control venting scheme has also been demonstrated for a high performance flat plate solar collectors [15].

Evacuated vacuum tube solar collectors represent a significant challenge with regard to stagnation control. Due to their low rates of heat loss, they have the potential to reach very high stagnation temperatures. In evacuated tube collectors with heat pipe based absorbers, one approach has been to isolate the heat pipe condenser when excessive temperatures are encountered [14]. This scheme stops the transfer of excess heat to the solar collector circulation loop but does not limit absorber temperatures in the vacuum tube. This may degrade collector performance if left for extended periods.

Alternative schemes for controlling temperatures in vacuum tube solar collectors have been previously investigated that were directed at increasing the rate of heat loss across the vacuum by introducing a desorbable gas, that can reversibly degrade the vacuum at elevated temperatures. The stagnation temperature of the system is thus limited in a controllable manner without significantly degrading the low temperature performance [16]. To date no commercial implementation of this approach has been widely demonstrated. Other approaches currently under study relate to the use of thermotropic glazings where transmission properties of the glazing material change with temperature [17]. The primary challenge with these approaches is related to lowering their cost.

5. Summary of stagnation control approaches

In reviewing the advantages and disadvantages of various stagnation control schemes it is worth considering the level of protection offered. For example, if stagnation can be dealt with in the solar collectors, such that heat is not transferred the solar collector loop or the system, then a high degree of system stagnation protection is achieved relative to approaches that expose the system components to high temperatures or pressures. In addition, to be viable in the market place, stagnation controls should be reliable, low-cost and operate passively, i.e., should not depend on external sources of power to operate. Considering these criteria, various stagnation control schemes currently used are compared in Table 2.

6. Conclusions

The effects of stagnation conditions can be devastating to solar thermal systems. Various approaches to minimizing the effects of stagnation condition have been developed and tried. Some proposed methods are not suitable for all system designs and applications. Factors such as storage and system capacity, load distribution, temperature and freeze protection requirements, influence the choice of stagnation control. In addition, passively operating systems, that do not depend on user or controller intervention, or that do not require external power to operate, would seem to offer significant advantages in terms of reliability.

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Table 2. Summary and overview of some collector and system level approaches to stagnation control

Stagnation Control Scheme	Protects Collectors?	Protects System Components?	Fail-safe Operation? (i.e., no external power needed)	Cost Impact?	Performance or durability Impact?
Drain-back or drain-down	No	Yes	Yes. (must be installed to drain completely if also used for freeze protection)	Pumping power consumption may be increased	Collector loop open to atmosphere may increase corrosion or fouling
Control based (e.g., night heat rejection, recirculation etc.)	Yes	Yes	No. (requires active control and pumping)	Not for hardware. (additional pump use & potential energy loss)	May result in available energy being dumped at night
Steam Back	Not always	Not always	Yes (careful design and placement of system components required)	Expansion tank may have to be oversized	Potential thermal shock/scalding on restart
Collector Venting (Integral to collector)	Yes (if carefully designed)	Yes (if carefully designed)	Yes (for thermally activated versions)	Modest hardware cost	May experience small performance penalty if not carefully implemented
Heat Waster on Collector loop	Yes	Yes	Some designs operate passively - others require power or pumps, fans etc.	Significant hardware cost	If powered may require aux. generators or PV
Heat pipe control (Evacuated-tube collector)	No	Yes	Yes (for thermally activated versions)	Modest Hardware cost	System may be inoperable for remainder of day

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